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EXPERIMENTS IN TEXTURE PERCEPTION

Annual Report

By

WHITMAN RICHARDS
DEPARTMENT OF PSYCHOLOGY

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASS. 02139

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Summary

Over the past year, our special graphics display has been used to examine several properties of texture perception. The most important result is the finding that most uniform textures can be simulated or "matched" by a very small number of variables, provided that these variables contain the basic elemental tokens of the display.

The number of these matching variables may be as small as three, and usually four is sufficient to produce excellent "texture metamers". Both linear, or one-dimensional luminance distributions and two-dimensional texture patterns are being studied.

Additional work has also been completed that examined the discriminability of different n-gram statistics for random-check textures. However, this approach does not appear to be so fruitful a method for studying texture perception as the method of "Generalized Colorimetry", which is outlined briefly in the first section of this report.

Our work to date indicates that the human observer is quite poor at discriminating textures. Hence a considerable saving in communicating texture information can be achieved through the use of texture metamers.

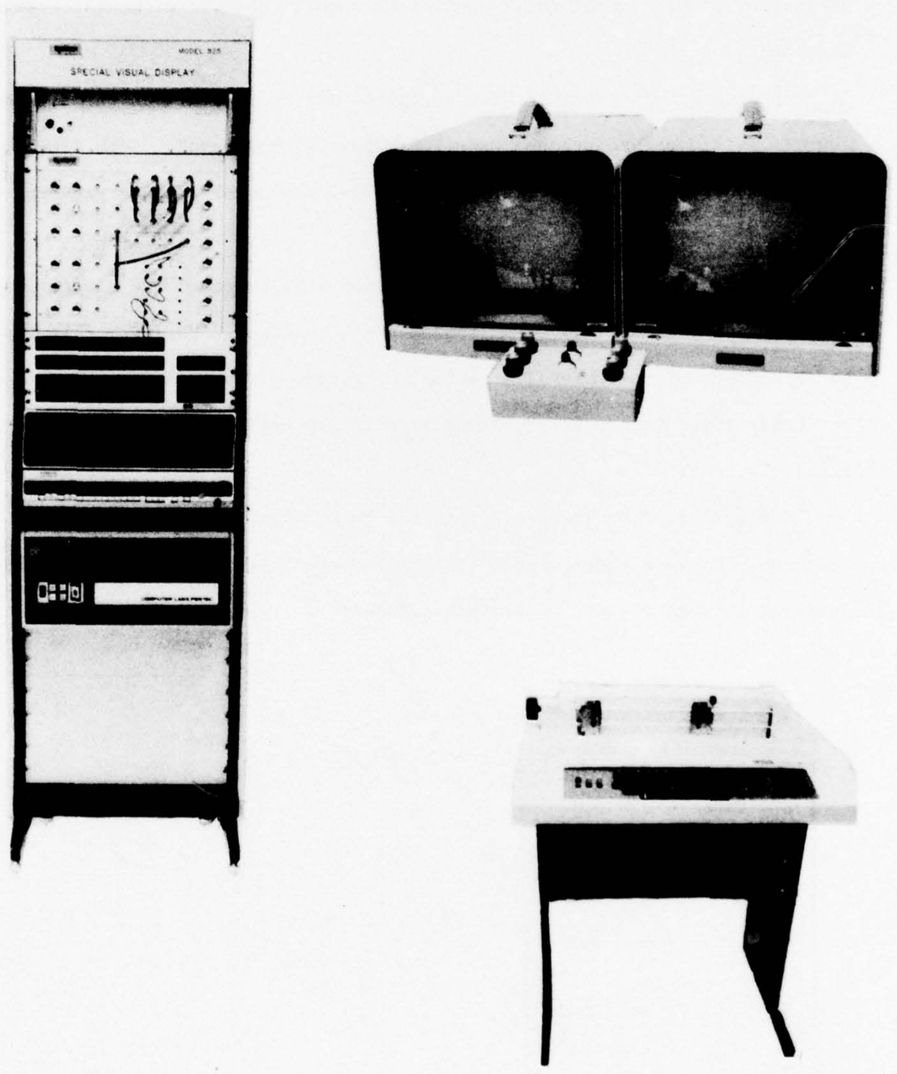

Figure 1

The special effects graphics display used to drive two TV monitors with 440 X 440 X 64 resolution. The device has 64K of 18 bit refresh memory, reprogrammable for use as PDP 11 core. The disk capacity is 2.5 million words. See Appendix for complete description of system.

Contents

Experiments in Texture Perception

I. Introduction

Texture, like color, is one of the primary properties of an object (Metzger, 1926; Koffka, 1935). Yet only few studies of the texture recognition process have been made before 1960. Since this time, two technological advances have occurred that have permitted visual scientists to begin to explore texture perception more fully. The first is the application of Fourier methods to visual perception. (Robson, 1966; Blakemore and Campbell, 1969) and the second is the availability of high-speed computers. The principal advantage gained by applying Fourier methods to vision has been the creation of a dimension - one of spatial frequency - into which the visual scientist can map the components of all patterns. Without this dimension, the study of texture perception has been handicapped in much the same way color vision studies would be impaired if the dimension of wavelength were not available. The second advance from computer technology allows one to now create easily many complex texture patterns having well-defined statistical or Fourier properties. The special graphics display takes advantage of both of these advances.

The novelty of our approach to human texture perception is that we are concerned only with describing textures that appear equivalent to one another. In the past, others have concentrated on the specification of the physical characteristics that will differentiate between all textures (See Bibliography). In contrast, our attempts to describe equivalent textures are quite analogous to the development of color science where the primary concern is to identify spectral compositions that appear equivalent to the human observer. Such energy distributions that are physically different but appear equivalent are called metamers. Our approach to texture perception is to describe such metamers.

II. Generalized Colorimetry

Our approach to texture perception uses a technique analogous to color-matching used so successfully in the study of color vision. "Generalized Colorimetry" is thus an extension of color-matching to the study of other sensory dimensions. To understand this generalized method, a review of the important characteristics of color-matching is helpful.

In the domain of color, a simplification in our understanding of wavelength processing by man was achieved not by reports of color sensations, but rather by the discovery of color blindnesses. The nature of these blindnesses could be characterized by a description of the number of functions needed to characterize all equivalences between different spectral lights (metamers). Given some simple assumptions about the nature of the phototransduction process, these functions could then be shown to relate to the different cone action spectra present in the retina. More strongly, the number of matching functions required to specify all color equivalences in the matching situation would correspond exactly to the number of different receptor pigments. When it was discovered that a small percentage of the population needed only two and not the usual three functions to describe all equivalences, color blindness could be recognized and described quantitatively in terms of a loss of receptor function (either absence or fusion).

The important features of this approach are:

i) Wavelength was available as a suitable dimension along which matching functions could be measured (Equivalence dimension)

ii) Unique and "stable" filters or "channels" were present, i.e. the different cone pigments themselves (Uniqueness property)

iii) Alternate sets of matching functions could be derived by adding or subtracting the members of the original set. (Additivity property).

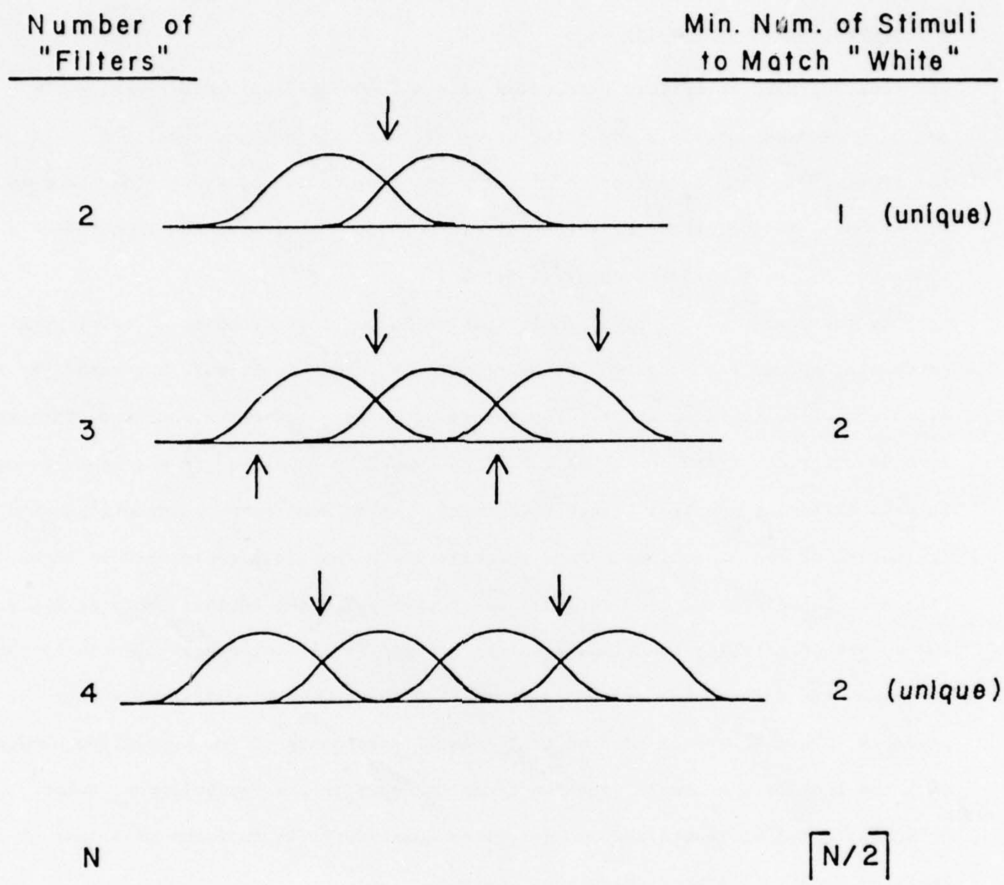

Fig. 2. Hypothetical sensitivity distributions of channels along a stimulus dimension skematized by the horizontal line. The positions of narrow-band stimuli are indicated by arrows.

iv) Color is an intensive variable, so spatial factors contribute minimally (Intensive property).

For the success of the generalized colorimetric method, a Dimension for constructing Equivalences or matches (i) must be available and (ii) the sensory attribute to be studied must have filters or channels that sample this dimension Uniquely. It is not necessary that Additivity (iii) hold exactly nor for the sensory variable to be Intensive (iv), although the interpretation is simpler when (iii) and (iv) are also valid.

Given the above assumptions, the generalized colorimetric technique proceeds in two steps: First, the minimum number of "functions" necessary to create an equivalence to a broad-band distribution is determined. This is equivalent to finding the minimum number of wavelengths needed to "match" a equivalence dimension and the matching functions are measured.

The first step provides an estimate of the number of matching functions that will be required to specify all equivalences along the chosen dimension. (This estimate corresponds to the minimum number of "channels" sampling that dimension). Referring to the top illustration of Fig. 2, the sensitivities of two filters or "channels" are illustrated along an arbitrary dimension characterized by a horizontal line. A broad-band stimulus with a flat distribution along the dimension would innervate both channels equally. But a narrow-band stimulus located at the intersection of the two sensitivity distributions (arrow) will also activate each channel equally. Hence for two filters, only one narrow-band stiumulus is needed to create an equivalent sensation, and this choice is unique for a given "white".

For three filters, two narrow-band stimuli are sufficient, as shown in our next illustration. However, an unlimited number of pairs can be found (only two are depicted). This is the case for color vision. For four filters or channels, the minimum solution is still two, but this choice is unique in that for any given broad-band distribution, only one pair can be found. Finally, in the general case,

for N filters or channels, the minimum number of narrow-band matching stimuli will be the integer value of N/2. If the solution does not require unique narrow-band stimuli, then the minimum number of sensory filters sampling the dimension is not greater than twice the number of matching narrow-band stimuli, less one.

These results apply regardless of the validity of the Additivity Property (iii) and regardless of the degree of overlap of the sensitivity functions for the individual "channels" (Richards, in preparation).

Following this preliminary analysis we then proceed to determine empirically the matching functions. In the past pilot experiments, these determinations have required considerable trial-and-error searching for the appropriate primaries. However, this search is greatly simplified by first making matches to the broad-band stimuli in the manner described above so that the minimum number of primaries is known at the outset.

To date, we have applied this technique to several sensory dimensions that include flicker (Richards, 1975), the orientation of texture elements (Riley, 1977), and spatial-frequency matches. Only the latter results will be summarized in this report.

III. One-Dimensional Textures

i.) "White"Noise Matches: Our preliminary white noise stimuli consist of up to 220 bars that have one of 63 randomly selected gray levels. Such a noise stimulus may be matched by randomly dispersed bars of the same width, where the gray level of each bar is chosen randomly from only three fixed gray levels. A metameric match to the noise stimulus may also be obtained using three suitably chosen square-wave gratings, each having a frequency approximately a prime ratio to the others to prevent periodicity. Neither of these matching stimuli need to be closely held - a range of either kind of triplets can be used to yield good matches to the "white" noise.

Our generalized colorimetry analysis would thus suggest that the perception of textures made up of complex luminance profiles is analyzed by not more than five "channels" or filters.

ii.) Narrow-band Matches: In fact, only four primary variables are necessary to match all one-dimensional textures degradeable into sinusoidal components. This result has been reported previously by us (Richards and Polit, 1975; also see previous annual report). To date we have collected texture-matching functions from three observers over the range from 1/4 to 30 c/deg and plan to include at least three more in our final report. These additional data are of interest to indicate the variance of the matches from one individual to the next.

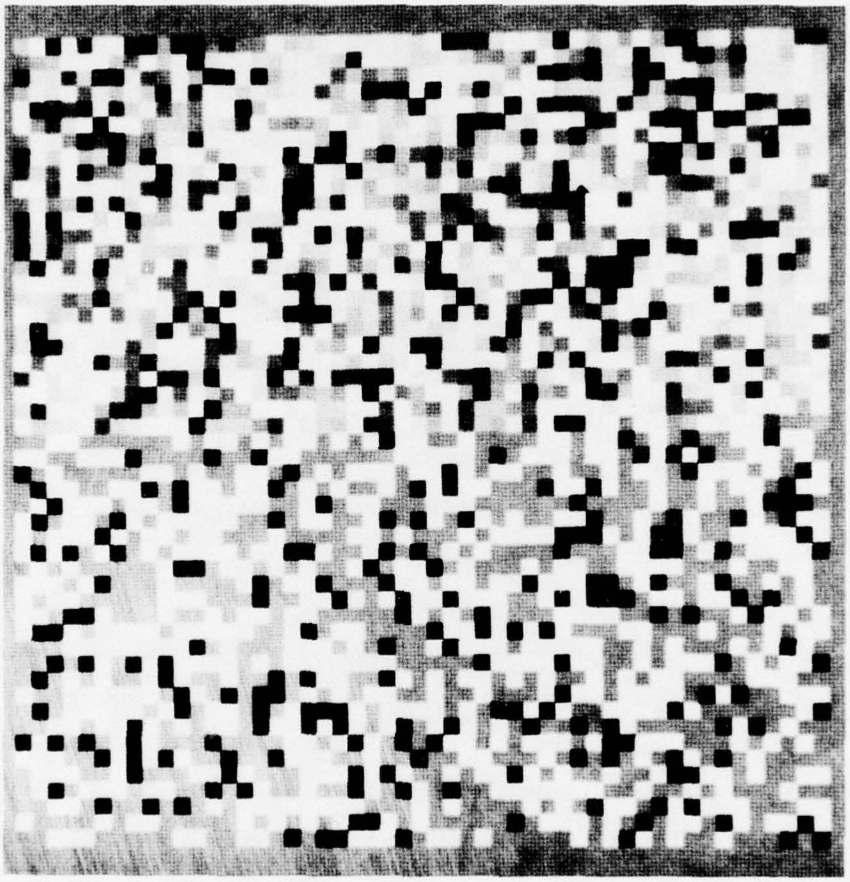

Fig. 3. The generalized colorimetric method applied to gray level encoding. The gray level of most of the checks in the pattern have one of 63 levels, chosen randomly. Which quadrant has only three gray levels represented? (Courtesy of M.D. Riley).

IV. Two-Dimensional Textures

Two-dimensional textures are patterns whose luminance profile may be defined by

$$L = L_o \, (1+M_x \cos 2\pi V_x X) \cdot (1+M_y \cos 2\pi V_y Y)$$

where M_x, M_y are the contrasts in the orthogonal X and Y directions, and V_x, V_y are the spatial frequencies. The sensitivity of the human visual system to such patterns seen both stationary or modulated temporally has been reported elsewhere (Richards, 1977). This report will indicate the progress that has been made in characterizing these patterns more simply from a perceptual viewpoint.

i.) "White" noise matches. Fig. 3 shows a two dimensional texture pattern of random checks with one ~~quadrant~~ half of the pattern having only three gray levels while the background has 63. (Courtesy of M. Riley). Clearly, three gray levels suffice for a two-dimensional white-noise match, just as in the one-dimensional case.

ii.) Narrow-band matches. Unlike one-dimensional textures, patterns containing the x,y product terms do not lend themselves to acceptable matches by using only four sinusoidal grating primaries. At least five and probably six primaries are needed if the luminance profile of the primary is sinusoidal. We believe the difficulty is that at high contrasts the two-dimensional products tend to generate checks or square-wave profiles that cannot be created with only a few sinusoids. For high-contrast, two-dimensional checks we thus plan on examining square-wave primaries, and also triangular-shaped waveforms. The latter may also provide satisfactory matches for one-dimensional sinusoidal textures.

V. N-Gram Statistics (with S. Purks)

This work is now reported elsewhere (Purks and Richards, 1977). Briefly, we describe a method for generating random-dot textures that provides statistical control of any adjacent point (n-grams), while leaving constant the statistics of shorter spans. The method thus allows the experimenter to isolate statistics of n-grams of any span length to determine the nature of their influence on texture discrimination. Variables that control phase are relatively unimportant. The most significant variables are constraints imposed upon span lengths less than 3 that regulate gray level and spatial frequency content. However, span lengths of 3 or greater may still influence discrimination by altering the distribution of the spatial frequency content.

Several of the experimental patterns suggest that the spatial frequency variable is important in texture perception. For example, the discrimination of different 4-gram statistics is subjectively based upon the visibility of runs, and this difference is enhanced by properly oriented blurring to cause streaking and to eliminate the high-frequency content introduced by the individual dots.

VI. Stereopsis with Random Checks

In the early sixties, Julesz (1962) generated random dot stereograms devoid of monocular cues. That is, when each stereogram was viewed monocularly the object seen in the correlated patterns was invisible. At this time, such stimuli were viewed as an advance in studying binocular vision for now the mechanism of stereopsis could be studied in isolation.

We have found, however, that depth perception elicited from random dot stereograms devoid of monocular cues is severely impaired when compared with similar stereograms that reveal the monocular contours. For transient stimuli, monocular contours appear necessary to elicit a range of depth sensations for different disparities, suggesting that monocular cue analysis is an integral component of the stereomechanism. Additional work is underway to determine the role of texture analyzing mechanisms in stereopsis. In particular, does the four-primary limitation on texture matches come before of after stereopsis?

VII. Projections

Texture is one of the primary properties of an object. Like color, texture is a quality that helps the human observer to define and identify objects. Yet we know very little about human texture perception. What is its basis? How good are we at identifying textures? Are we as good as a Fourier pattern analyser? At present, the most important aspect of the research suggests that texture analysis is performed by only three or four "filters". For example, all (one-dimensional) textures may be completely specified in terms of only four primaries, at least over the range of focal vision. Such a specification will describe all equivalences between textures that are constructed from similar basis (i.e. such as sine-wave or square-wave gratings or probably even line elements). This is a nontrivial accomplishment. In the domain of color perception, if it were necessary to describe all colors in terms of its precise wavelength composition, then the transmission of chromatic information would not have become a feasible possibility. The fact that the human observer filters the wavelength spectrum allows us to build economical communication systems for chromatic information. By the same token, because the human observer analyses textures on the basis of only a few filters, then a considerable saving in the transmission of texture information may be gained. This practical benefit far outweighs, but in no way diminishes the further gains that we will achieve in our understanding of the human visual system.

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IX. Appendix

Special Graphics System

In order to generate texture patterns from their spatial frequency (Fourier) components, we have designed and have built a special graphics display. This display allows us to generate a 440 x 440 x 6 bit brightness pattern consisting of complex (computer-generated) sinusoids whose contrast may be altered every 20 msec. Both the sums and products of up to six components may be displayed with variable contrast.

More specifically, the special visual display consists of 9 subsystems as follows:

1. Monitors: Conrac SNA 17/C (2)
   Monochrome television monitors
2. Operator Controls: Two channels, each with independent control of three sinusoidal or other component amplitudes and the a(x)*a(y) product term. Control boxes are on extension cables for convenience and flexibility of location. A six-channel A/D converter digitizes the control settings for input to the computer.
3. Function Table Computer: A dedicated PDP 11/10 Minicomputer is used to monitor the operator controls and calculate a(u) and b(u) function tables in accordance with the operator control settings, where

$$a(u) = \sum_{i=1}^{3} A_1 \sin(2\pi f_i u + \phi_i)$$

$$b(u) = \sum_{i=1}^{3} B_i \sin(2\pi f_i u + \phi_i)$$

4. Video Function Generators: Two identical custom designed video generators are provided to store the computed function tables and generate a video luminance signal of the form:

$$L_A(X,Y) = 1 + a(x) + a(y) + K_A a(x)\ a(y)$$

$$L_B(X,Y) = 1 + b(x) + b(y) + K_B b(x)\ b(y)$$

Provision is made for adding an external video signal.

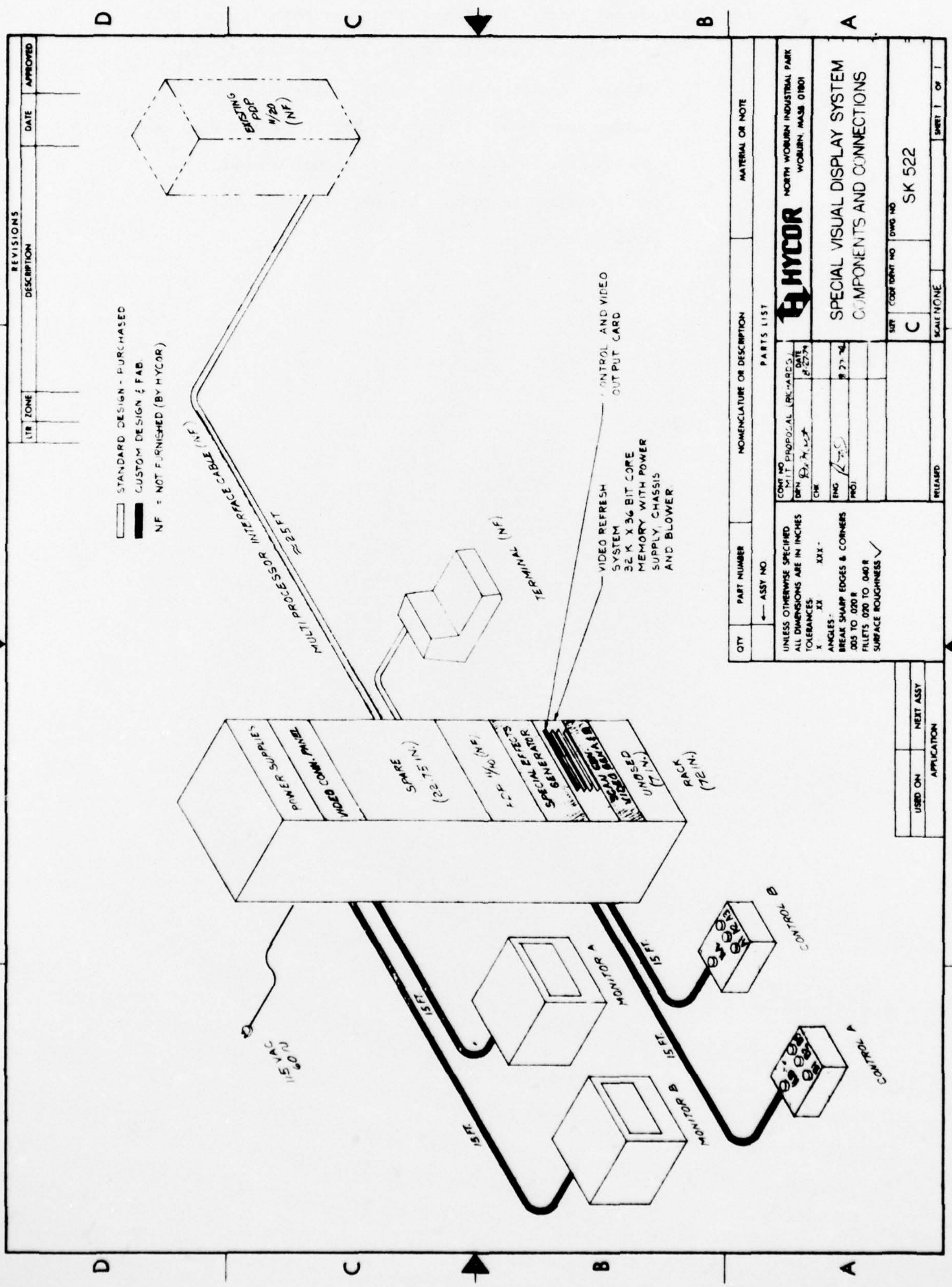
5. Scan Generator: A custom designed digital scan generator generates rastor coordinates, synchronizing signals and control signals.

6. Video Refresh System: A custom-designed video refresh system is provided to allow an arbitrary two-dimensional pattern to be added to the texture display. The refresh system employs a standard core memory of 32,768 thirty-six bit words and can store 196,608 picture elements (pixels) with 6 bit (64 level) gray scale.

The EMM Micromemory 3000 series has been used for the core memory. Four 3000DD (16K x 18 bit) cards are mounted in a 5 1/4" high chassis together with a control and video output card, power supply and cooling fans. The control card circuit provides an alternate mode of operation in which four 108 x 108 checkerboard patterns can be stored and refreshed. The PDP-11/10 has control of mode selection and can select which of the four patterns is to be displayed.

If in the future, the video refresh capability should be no longer needed, the core memory can be easily converted on site to a general purpose RAM. EMM offers a Unibus interface for the Micromemory 3000 series. (See part (ii) of this section).

7. <u>Video Interconnect Panel</u>: A video interconnect panel is available to permit easy and flexible interconnection of video signals. The panel also contains eight adjustable DC voltage sources and a video integrator for use with the special effects generator and video multiplexer. The prints describing these components in more detail are given in Appendix I.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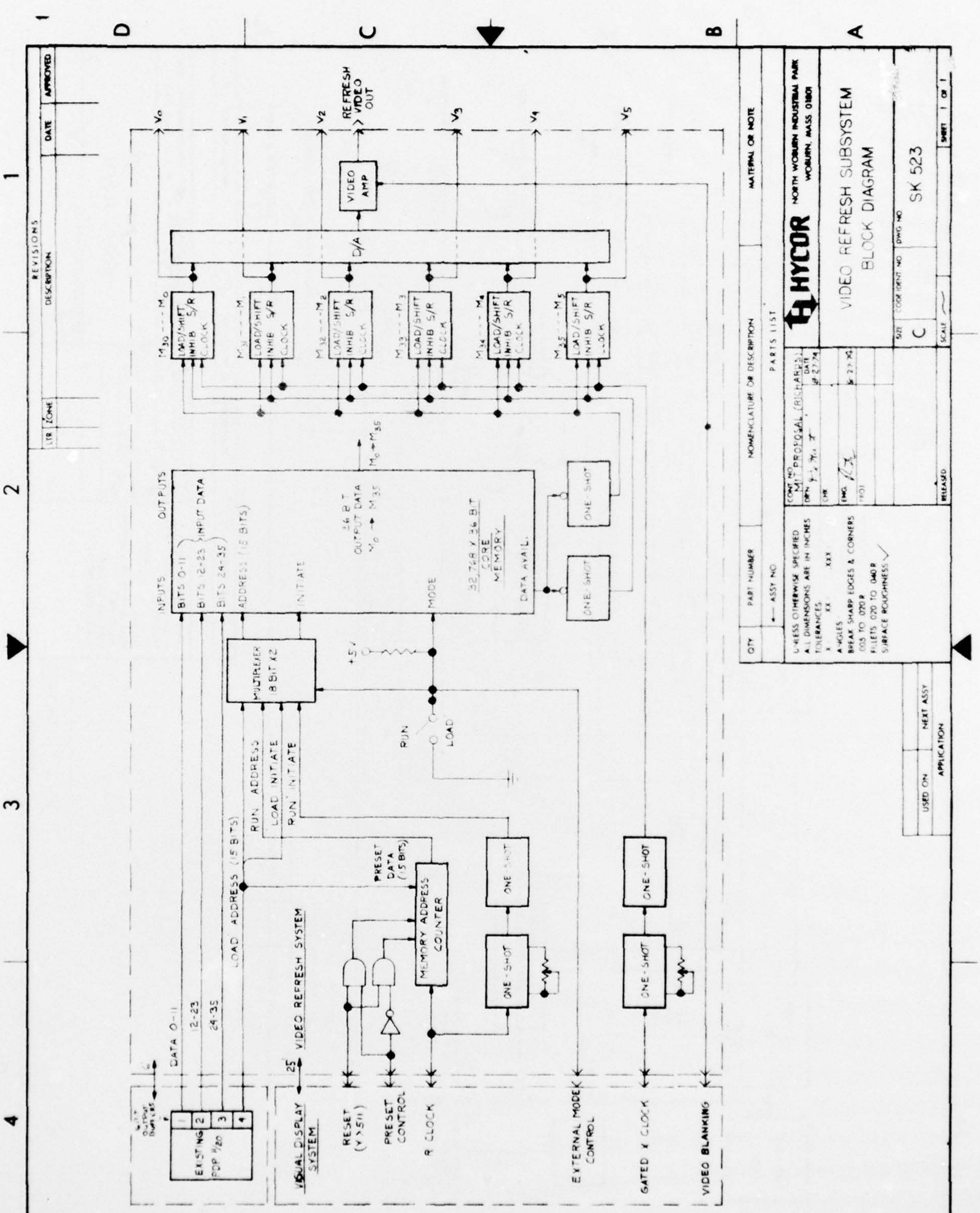
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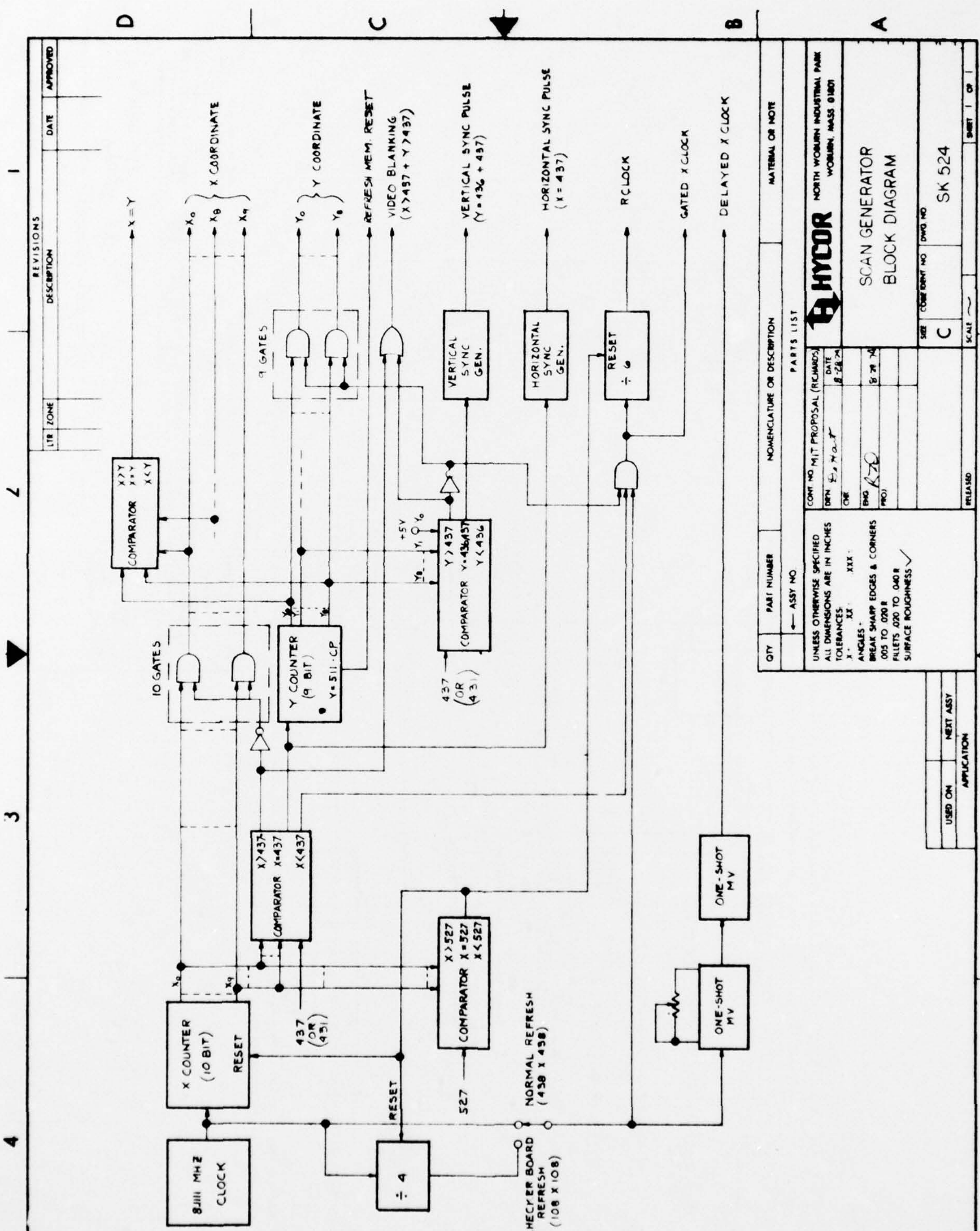
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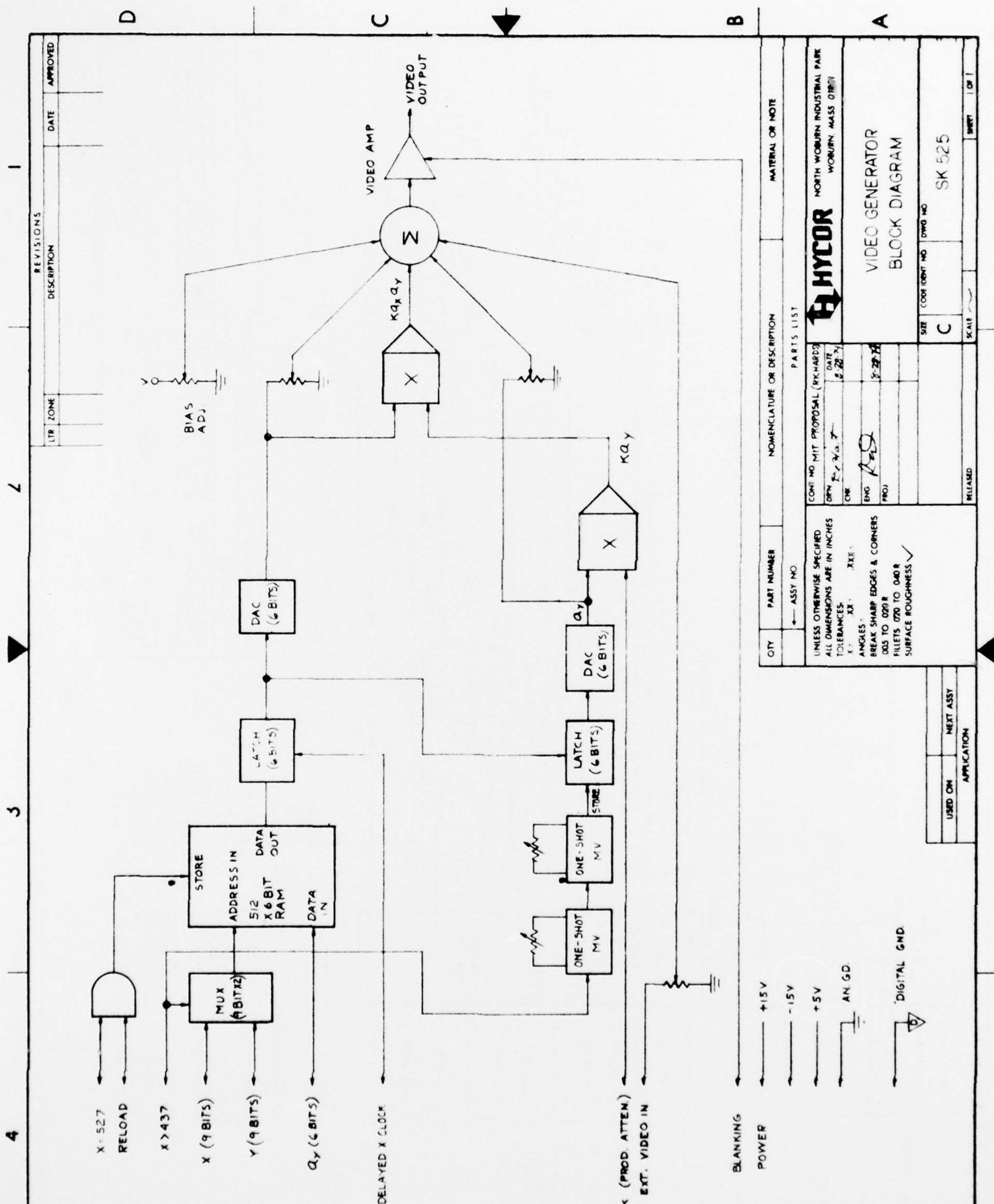

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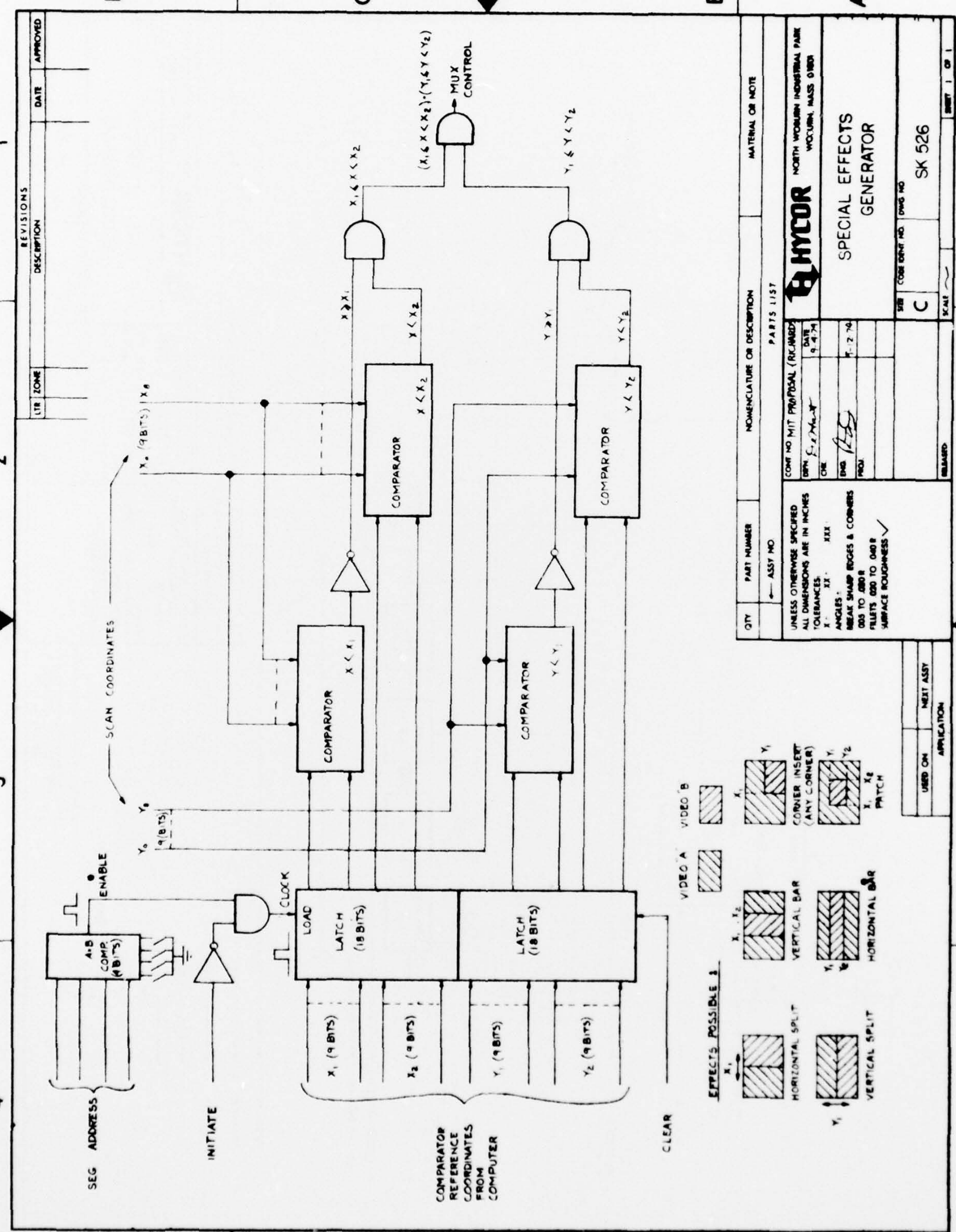
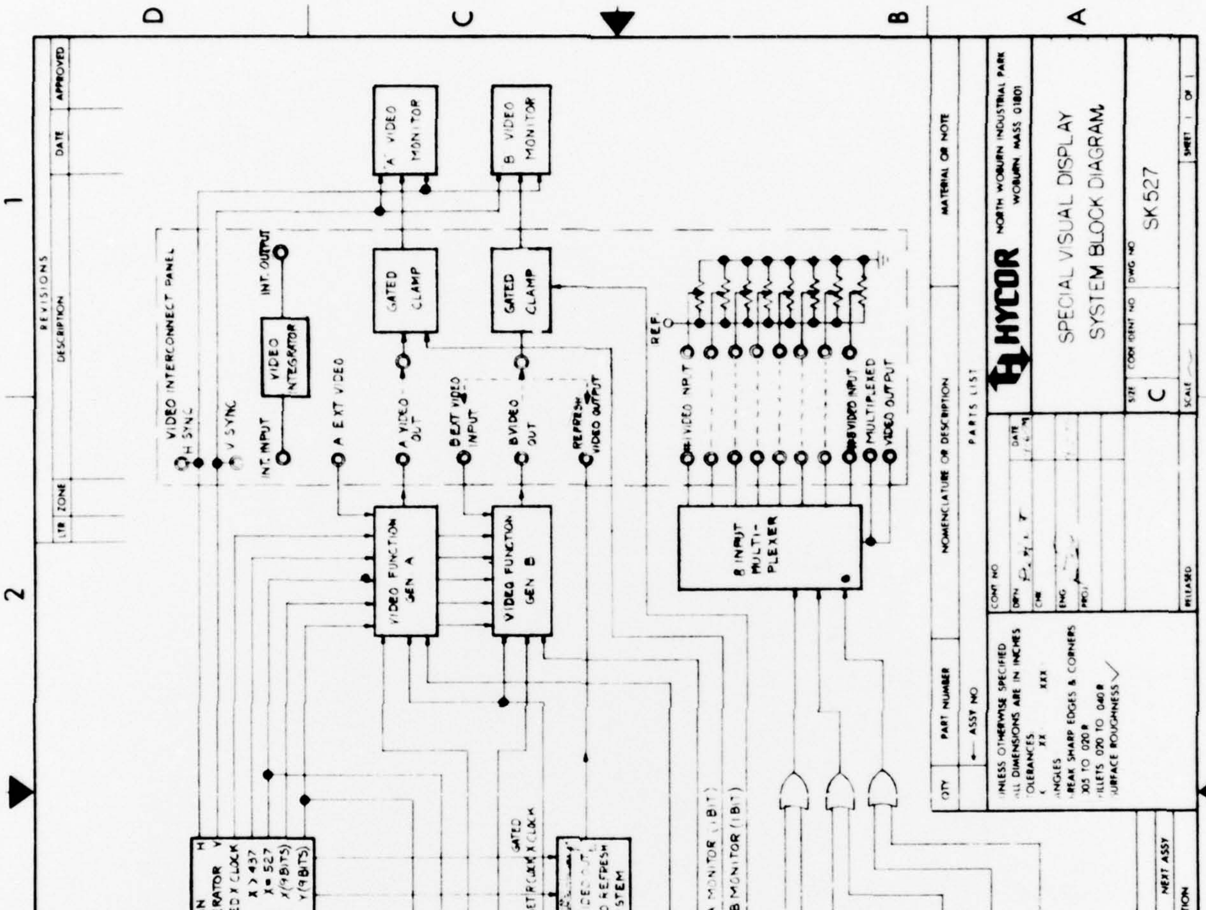
NEXT ASSY
APPLICATION


SEG ADDRESS
INITIATE
COMPARATOR REFERENCE COORDINATES FROM COMPUTER
CLEAR
A=B COMP (4 BITS)
ENABLE
CLOCK
LOAD
LATCH (18 BITS)
LATCH (18 BITS)
X_1 (9 BITS)
X_2 (9 BITS)
Y_1 (9 BITS)
Y_2 (9 BITS)
SCAN COORDINATES
Y_0 Y_8 (9 BITS)
X_0 (9 BITS) X_8
COMPARATOR
$X < X_1$
$X < X_2$
$Y < Y_1$
$Y < Y_2$
$X \geq X_1$
$Y \geq Y_1$
$X_1 \leq X < X_2$
$Y_1 \leq Y < Y_2$
MUX CONTROL
$(X_1 \leq X < X_2) \cdot (Y_1 \leq Y < Y_2)$
EFFECTS POSSIBLE:
HORIZONTAL SPLIT
VERTICAL SPLIT
VERTICAL BAR
HORIZONTAL BAR
VIDEO A
VIDEO B
CORNER INSERT (ANY CORNER)
PATCH
REVISIONS
LTR
ZONE
DESCRIPTION
DATE
APPROVED
QTY
PART NUMBER
NOMENCLATURE OR DESCRIPTION
MATERIAL OR NOTE
PARTS LIST
ASSY NO
UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS ARE IN INCHES
TOLERANCES
ANGLES
BREAK SHARP EDGES & CORNERS
SURFACE ROUGHNESS
CONT NO MIT PROPOSAL (RICHARD)
HYCOR
NORTH WOBURN INDUSTRIAL PARK WOBURN, MASS 01801
SPECIAL EFFECTS GENERATOR
SIZE
C
SK 526
SHEET 1 OF 1
USED ON
NEXT ASSY
APPLICATION



HYCOR
NORTH WOBURN INDUSTRIAL PARK WOBURN MASS 01801
SPECIAL VISUAL DISPLAY
SYSTEM BLOCK DIAGRAM
SK527
REVISIONS
PARTS LIST
TERMINAL (NF)
READER (NF)
PDP 11/20 (NF)
MULTIPROCESSOR INTERFACE (NF)
CONTROL BOX A
CONTROL BOX B
A/D(6)
MINICOMPUTER PDP 11/10 (NF)
TERMINAL INTERFACE (NF)
TAPE READER INTERFACE (NF)
UNIBUS INTERFACE (NF)
SCAN GENERATOR
DELAYED X CLOCK
X = 527
VIDEO FUNCTION GEN A
VIDEO FUNCTION GEN B
VIDEO REFRESH SYSTEM
A VIDEO MONITOR
B VIDEO MONITOR
GATED CLAMP
VIDEO INTEGRATOR
VIDEO INTERCONNECT PANEL
H SYNC
V SYNC
INT. INPUT
INT. OUTPUT
A EXT VIDEO
A VIDEO OUT
B EXT VIDEO INPUT
B VIDEO OUT
REFRESH VIDEO OUTPUT
8 INPUT MULTI-PLEXER
MULTIPLEXED VIDEO OUTPUT
REF
INTERRUPT
RELOAD A (1 BIT)
RELOAD B (1 BIT)
DATA (36 BITS)
ADDRESS (12 BITS)
PRESET (1 BIT)
CONTROL
BLANK A MONITOR (1 BIT)
BLANK B MONITOR (1 BIT)
SPECIAL EFFECTS INTERCONNECT PANEL
SEG 1
SEG 2
SEG 3
SEG 4
SEG 5
SEG 6
SEG INITIATE (1 BIT)
SEG CLEAR (1 BIT)
ADDRESS (4 BITS)
STANDARD DESIGN - PURCHASED
CUSTOM DESIGN & FAB.
NF - NOT FURNISHED (BY HYCOR)
USED ON
NEXT ASSY
APPLICATION

Unclassified

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Over the past year, our special graphics display has been used to examine several properties of texture perception. The most important result is the finding that most uniform textures can be simulated or "matched" by a very small number of variables, provided that these variables contain the basic elemental tokens of the display.

The number of these matching variables may be as small as three, and usually four is sufficient to produce excellent "texture metamers". Both

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linear, or one-dimensional luminance distributions and two-dimensional texture patterns are being studied.

Additional work has also been completed that examined the discriminibility of different n-gram statistics for random-check textures. However, this approach does not appear to be so fruitful a method for studying texture perception as the method of "Generalized Colorimetry", which is outlined briefly in the first section of this report.

Our work to date indicates that the human observer is quite poor at discriminating textures. Hence a considerable saving in communicating texture information can be achieved through the use of texture metamers.

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